

Evidence for an anomalous like-sign dimuon charge asymmetry

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We measure the charge asymmetry $A \equiv (N^{++} - N^{--})/(N^{++} + N^{--})$ of like-sign dimuon events in 6.1 fb^{-1} of $p\bar{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96 \text{ TeV}$ at the Fermilab Tevatron collider. From A we extract the like-sign dimuon charge asymmetry in semileptonic b -hadron decays: $A_{\text{sl}}^b = -0.00957 \pm 0.00251 (\text{stat}) \pm 0.00146 (\text{sys})$. It differs by 3.2 standard deviations from the standard model prediction $A_{\text{sl}}^b(\text{SM}) = (-2.3_{-0.6}^{+0.5}) \times 10^{-4}$, and provides first evidence of anomalous CP violation in the mixing of neutral B mesons.

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Studies of particle production and decay under the reversal of discrete symmetries (charge, parity and time) have yielded considerable insight into the structure of theories that describe high energy phenomena. Of particular interest is the observation of CP violation, a phenomenon well established in the K^0 and B_d^0 systems, but not in the B_s^0 system where the effects of CP -violation are expected to be small in the standard model (SM) [1].

A review of the experimental results and of the theoretical framework for describing CP violation in neutral mesons decays can be found in Ref. [2]. The violation of CP symmetry is a necessary condition for baryogenesis, the process thought to be responsible for the matter-antimatter asymmetry of the universe [3]. However, the observed level of CP violation in the K^0 and B_d^0 systems is not sufficient to accommodate this asymmetry, suggesting the presence of additional sources of CP violation beyond the SM [4].

This Letter and a more detailed Article [5] present a measurement of the charge asymmetry for like-sign muon pairs. The data, corresponding to an integrated luminosity of 6.1 fb^{-1} , were recorded with the D0 detector [6] at the Fermilab Tevatron proton-antiproton ($p\bar{p}$) collider, operating at a center-of-mass energy of 1.96 TeV. The

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D0 experiment is well suited to the investigation of the small effects of CP violation because the periodic reversal of the D0 solenoid and toroid magnetic field polarities results in a cancellation of most detector-related asymmetries. In addition, the $p\bar{p}$ initial state is a CP eigenstate, and the high center-of-mass energy provides access to mass states beyond the reach of the B -factories running at $\sqrt{s} = M(\Upsilon(4S))$.

The like-sign dimuon charge asymmetry A is defined as

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}, \quad (1)$$

where N^{++} and N^{--} represent the number of events in which the two muons of highest transverse momentum, satisfying the kinematic selections described below, have the same positive or negative charges. After removing contributions from background and from remaining detector effects, any residual asymmetry is assumed to arise solely from the mixing of B_q^0 ($q = d, s$) mesons (via $B_q^0 \leftrightarrow \bar{B}_q^0$ oscillations) that later decay semileptonically. This corrected asymmetry A_{sl}^b is defined as

$$A_{\text{sl}}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}, \quad (2)$$

where N_b^{++} and N_b^{--} represent the number of events containing two b -hadrons decaying semileptonically into two positive or two negative muons, respectively. Assuming CPT invariance, each neutral B_q^0 meson contributes a term to this asymmetry

$$A_{\text{sl}}^b = \beta_d a_{\text{sl}}^d + \beta_s a_{\text{sl}}^s, \quad (3)$$

$$\text{with } a_{\text{sl}}^q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan \phi_q, \quad (4)$$

where ϕ_q is the CP -violating phase, and ΔM_q and $\Delta\Gamma_q$ are the mass and width differences between the eigenstates of the propagation matrices of the neutral B_q^0 mesons. The values of $\beta_d = 0.506 \pm 0.043$ and $\beta_s = 0.494 \pm 0.043$ are taken from previous measurements [2]. The SM predicts $\phi_s = 0.0042 \pm 0.0014$, $\phi_d = -0.091_{-0.038}^{+0.026}$, $\Delta\Gamma_d = (26.7_{-6.5}^{+5.8}) \times 10^{-4} \text{ ps}^{-1}$, $\Delta\Gamma_s = (9.6 \pm 3.9) \times 10^{-2} \text{ ps}^{-1}$, $a_{\text{sl}}^d = (-4.8_{-1.2}^{+1.0}) \times 10^{-4}$ and $a_{\text{sl}}^s = (2.06 \pm 0.57) \times 10^{-5}$ [1]. Deviations of the expected asymmetries from zero are negligible compared to the present experimental sensitivity, and correspond to a small value for A_{sl}^b [1]:

$$A_{\text{sl}}^b(\text{SM}) = (-2.3_{-0.6}^{+0.5}) \times 10^{-4}. \quad (5)$$

Extensions of the SM containing additional contributions to the Feynman “box” diagrams responsible for B_q^0 mixing can result in larger values of ϕ_q or $\Delta\Gamma_q$ [7–11]. Measurements of A_{sl}^b , ϕ_q or $\Delta\Gamma_q$ that differ significantly from the expectations of the SM would therefore be indicative of the presence of physics beyond the SM.

At the Fermilab Tevatron collider, b quarks are produced mainly in $b\bar{b}$ pairs. In like-sign dimuon events, one muon arises from direct semileptonic decay, e.g., $b \rightarrow \mu^- X$, of a \bar{B}_q^0 or B^- meson, and the other muon from a $B_q^0 \leftrightarrow \bar{B}_q^0$ oscillation followed, in this example, by a semileptonic decay of the \bar{B}_q^0 meson, $\bar{B}_q^0 \rightarrow \mu^- X$. The main background for these measurements arises from events with at least one muon from kaon or pion decays or from the sequential decay of b quarks, $b \rightarrow c \rightarrow \mu^+ X$. The most important background asymmetry arises from the fact that K^+ and K^- mesons interact differently with the material of the detector, and thus their decay rates into positive and negative muons are not identical.

The asymmetry A_{sl}^b can also be obtained from the measurement of the charge asymmetry a_{sl}^b in semileptonic decays of b quarks to muons of “wrong charge”, i.e., a muon of charge opposite to the sign of the charge of the original b quark, induced through $B_q^0 \leftrightarrow \bar{B}_q^0$ oscillations [12]:

$$a_{\text{sl}}^b \equiv \frac{\Gamma(\bar{B} \rightarrow B \rightarrow \mu^+ X) - \Gamma(B \rightarrow \bar{B} \rightarrow \mu^- X)}{\Gamma(\bar{B} \rightarrow B \rightarrow \mu^+ X) + \Gamma(B \rightarrow \bar{B} \rightarrow \mu^- X)} = A_{\text{sl}}^b. \quad (6)$$

The asymmetry a_{sl}^b can be measured from the inclusive muon charge asymmetry

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}, \quad (7)$$

where n^+ and n^- correspond to the number of positive and negative muons satisfying the kinematic selections. For the asymmetry a , the signal comes from B_q^0 mixing, followed by the semileptonic decay. In addition to the background already considered for A , the direct production of c quark pairs followed by their semileptonic decays constitutes an additional source of muons contributing to a .

We define all muons from weak decays of b and c quarks as signal, and use the branching fractions and momentum spectra of particles in the decay chains that produce such muons to determine the dilution of the A_{sl}^b asymmetry in the observed asymmetry of the signal component. The dilutions, defined as the coefficients which relate the signal asymmetries to A_{sl}^b , are 0.070 ± 0.006 and 0.486 ± 0.032 for the inclusive muon and for the like-sign dimuon signal asymmetries, respectively. The difference in the dilution coefficients arises because the presence of the second muon with the same charge acts as a flavor tag. Therefore, the asymmetry A is far more sensitive to A_{sl}^b than a .

We measure the asymmetries A and a in the like-sign dimuon and inclusive muon data, respectively. These have different contributions from background processes and from detector asymmetries, which are measured directly in data as a function of the muon transverse momenta, and are used to correct the measured asymmetries. After applying all corrections, the only expected source of residual asymmetry in both the inclusive muon and dimuon samples is the asymmetry A_{sl}^b . Given the difference in sensitivity between A and a and the fact that

the asymmetry a is dominated by detector effects, we do not take a weighted average of the two determinations of A_{sl}^b . Instead, we use the measurement of a to constrain the background contributions to A , thereby achieving a further reduction of the total uncertainty on A_{sl}^b . This is possible because the detector effects and their related systematic uncertainties largely cancel in the linear combination of A and a .

The inclusive muon and like-sign dimuon samples are obtained from data collected with single and dimuon triggers, respectively. Charged particles with transverse momentum in the range $1.5 < p_T < 25$ GeV and with pseudorapidity $|\eta| < 2.2$ [13] are considered as muon candidates. The upper limit on p_T is applied to suppress the contribution of muons from W and Z boson decays. To ensure that the muon candidate passes through the detector, including all three layers of the muon system, we require either $p_T > 4.2$ GeV or a longitudinal momentum component $|p_z| > 6.4$ GeV. Muon candidates are selected by matching central tracks with a segment reconstructed in the muon system and by applying tight quality requirements aimed at reducing false matching and background from cosmic rays and beam halo. The transverse impact parameter of the muon track relative to the reconstructed $p\bar{p}$ interaction vertex must be smaller than 0.3 cm, with the longitudinal distance from the point of closest approach to this vertex smaller than 0.5 cm. Strict quality requirements are also applied to the tracks and to the reconstructed $p\bar{p}$ interaction vertex. The inclusive muon sample contains all muons passing the selection requirements. If an event contains more than one muon, each muon is included in the inclusive muon sample. The like-sign dimuon sample contains all events with at least two muon candidates with the same charge. These two muons are required to have an invariant mass greater than 2.8 GeV to minimize the number of events in which both muons originate from the same b quark.

Muons from decays of charged kaons and pions and from incomplete absorption of hadrons that penetrate the calorimeter and reach the muon detectors (“punch-through”), as well as false matches of central tracks to segments reconstructed in the outer muon detector, are considered as detector backgrounds. We use data to measure the fraction of each source of background in both the dimuon and inclusive muon samples, and the corresponding asymmetries. Data are also used to determine the intrinsic charge-detection asymmetry of the D0 detector. Since the interaction length of the K^+ meson is greater than that of the K^- meson [2], kaons provide a positive contribution to the asymmetries A and a . The asymmetries for other background sources (pions, protons and falsely reconstructed tracks) are at least a factor of ten smaller.

The asymmetry for kaon tracks that are eventually misidentified as muons ($K \rightarrow \mu$ tracks) is measured in data using $K^{*0} \rightarrow K^\pm \pi^\mp$ and $\phi \rightarrow K^+ K^-$ decays. For both channels we select muon candidates from the entire inclusive muon sample and examine mass distributions

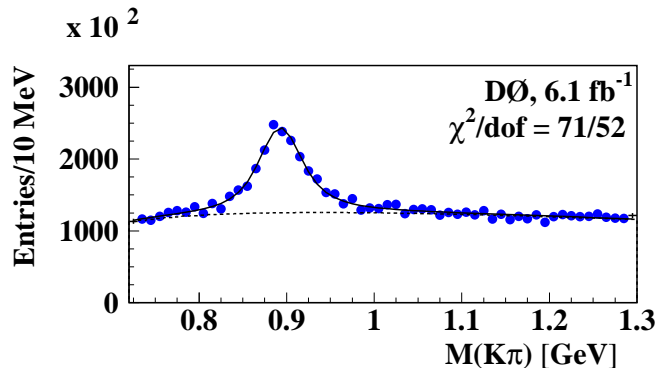


FIG. 1: The difference in the number of events for the $K^+ \pi^-$ and $K^- \pi^+$ mass distributions of K^{*0} candidates in the inclusive muon sample. The solid line represents the result of the fit, while the dashed line shows the background contribution.

separately for events with $K^+ \rightarrow \mu^+$ and $K^- \rightarrow \mu^-$ tracks, extracting the sum and the difference in the number of K^{*0} or ϕ meson decays containing positive or negative $K \rightarrow \mu$ tracks. The distribution of this difference as a function of the invariant mass of the K^{*0} candidates is shown in Fig. 1. The resulting asymmetry is corrected using simulations [5] for the fraction of kaons ($\approx 6\%$) that decay prior to being reconstructed. Similarly, the asymmetry for pion or proton tracks misidentified as muons are measured using samples of $K_S \rightarrow \pi^+ \pi^-$ and $\Lambda \rightarrow p \pi^-$ decays, respectively.

The fraction of muons from kaons is also determined from the $K^{*0} \rightarrow K^+ \pi^-$ sample. The fraction of all kaons arising from K^{*0} decay is taken from the observed $K^{*\pm} \rightarrow K_S \pi^\pm$ decays using the assumption of isospin invariance, which is validated in data [2]. The probability of identifying the associated π^\pm in the K^{*0} decay is taken to be the same as in $K^{*\pm}$, as is confirmed by simulation. The fractions of pions and protons associated with identified muons, relative to the fraction of muons from kaons, are estimated using the decays $K_S \rightarrow \pi^+ \pi^-$, $\phi \rightarrow K^+ K^-$, and $\Lambda \rightarrow p \pi^-$ decays, and the spectra and multiplicities of pions, kaons and protons from simulation.

After subtracting the muons originating from kaons, pions and protons, we find the fraction of muons in the inclusive muon sample from prompt sources constituting the signal sample (heavy flavor) to be 0.581 ± 0.014 (stat) ± 0.039 (syst). The signal fraction arising from prompt sources for the like-sign dimuon sample, after subtracting the contribution from events where one or both muons are background, is 0.665 ± 0.016 (stat) ± 0.033 (syst).

Table III of Ref. [14] lists all significant contributions to the dimuon charge asymmetry caused by detector effects. The largest of these is $\approx 3\%$. The reversal of both solenoid and toroid magnet polarities suppresses many detector effects, reducing thereby any charge asymmetry introduced by track reconstruction and muon identifica-

tion considerably [14]. The small residual reconstruction asymmetry is measured using a sample of $J/\psi \rightarrow \mu^+\mu^-$ decays reconstructed from two central detector tracks, with at least one matching a track segment in the muon detector. This measurement is performed as a function of the muon p_T and indicates a residual detector asymmetry of order 10^{-3} .

The uncorrected asymmetries a and A are obtained by counting the number of events of each charge in the inclusive muon and like-sign dimuon samples, respectively. There are 1.495×10^9 muons in the inclusive muon sample and 3.731×10^6 events in the like-sign dimuon sample. The uncorrected asymmetries are

$$a = +0.00955 \pm 0.00003 \text{ (stat)}, \quad (8)$$

$$A = +0.00564 \pm 0.00053 \text{ (stat)}. \quad (9)$$

After correcting for background and for the dilutions of the A_{sl}^b asymmetry in the observed asymmetries of the signal component, we obtain

$$A_{\text{sl}}^b = +0.0094 \pm 0.0112 \text{ (stat)} \pm 0.0214 \text{ (syst)} \quad (10)$$

from the inclusive muon sample and

$$A_{\text{sl}}^b = -0.00736 \pm 0.00266 \text{ (stat)} \pm 0.00305 \text{ (syst)} \quad (11)$$

from the like-sign dimuon sample. The uncertainties on the measurement obtained from the like-sign dimuon sample are much smaller, as expected from the factor of seven difference in the dilution coefficients that relate the signal asymmetries to A_{sl}^b in the two samples. Since the same background processes contribute to the uncorrected asymmetries a and A , their uncertainties are strongly correlated. We take advantage of this correlation to obtain a single optimized value of A_{sl}^b with higher precision, by using a linear combination of the uncorrected asymmetries

$$A' \equiv A - \alpha a. \quad (12)$$

We scan the coefficient α in order to minimize the total uncertainty on the value of A_{sl}^b , which occurs when $\alpha = 0.959$. The corresponding final result for the asymmetry A_{sl}^b is:

$$A_{\text{sl}}^b = -0.00957 \pm 0.00251 \text{ (stat)} \pm 0.00146 \text{ (syst)}. \quad (13)$$

It differs by 3.2 standard deviations from the SM prediction for A_{sl}^b of Eq. (5). The contributions to the total uncertainty of A_{sl}^b in Eqs. (10), (11) and (13) are listed in Table I, and the result in Eq. (13) is dominated by statistical uncertainties.

Several consistency checks are performed by dividing the data into smaller samples using additional selections based on data taking periods, muon and track quality requirements, and changing the requirements on impact parameter, transverse momentum, polar angle and rapidity of the muons. The resulting variations of A_{sl}^b are statistically consistent with the result of Eq. 13, even

TABLE I: Sources of uncertainty on A_{sl}^b in Eqs. (10), (11), and (13). The first eight rows correspond to statistical uncertainties and the next three rows to systematic uncertainties.

Source	$\delta(A_{\text{sl}}^b)(10)$	$\delta(A_{\text{sl}}^b)(11)$	$\delta(A_{\text{sl}}^b)(13)$
A or a (stat)	0.00066	0.00159	0.00179
K fraction (stat)	0.00222	0.00123	0.00140
π fraction	0.00234	0.00038	0.00010
p fraction	0.00301	0.00044	0.00011
K asymmetry	0.00410	0.00076	0.00061
π asymmetry	0.00699	0.00086	0.00035
p asymmetry	0.00478	0.00054	0.00001
detector asymmetry	0.00405	0.00105	0.00077
K fraction (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
A_{sl}^b dilution	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	0.02415	0.00405	0.00290

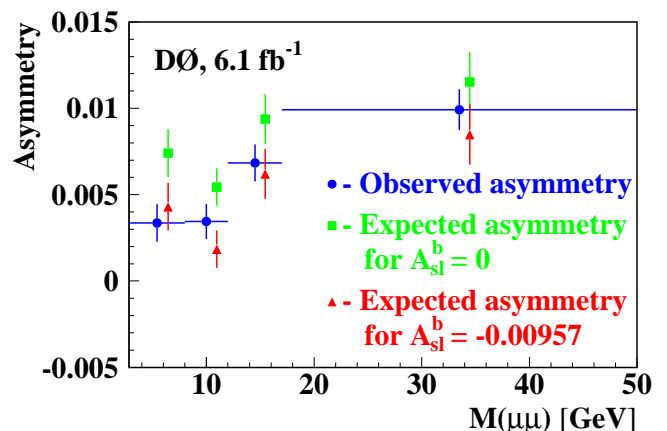


FIG. 2: (Color online) The observed and expected like-sign dimuon charge asymmetry A as a function of dimuon invariant mass. The expected asymmetry is shown for $A_{\text{sl}}^b=0$ and $A_{\text{sl}}^b=-0.00957$.

if the individual values of the uncorrected asymmetries A and a vary widely between the different samples due to changes in the background contributions. Both the size and the dependence on the muon momentum of the asymmetry a , which is dominated by background, are reproduced correctly through measurements of the background fractions and asymmetries. Similarly, the dependence of the like-sign dimuon asymmetry on the dimuon invariant mass observed in data, as shown in Fig. 2, is reproduced by expectations when A_{sl}^b is fixed to its measured value, while there are significant discrepancies if $A_{\text{sl}}^b = 0$ is assumed.

The measured value of A_{sl}^b places a constraint on the charge asymmetries in semileptonic decays of B_d^0 and B_s^0 mesons and on the CP -violating phases of the B_d^0 and

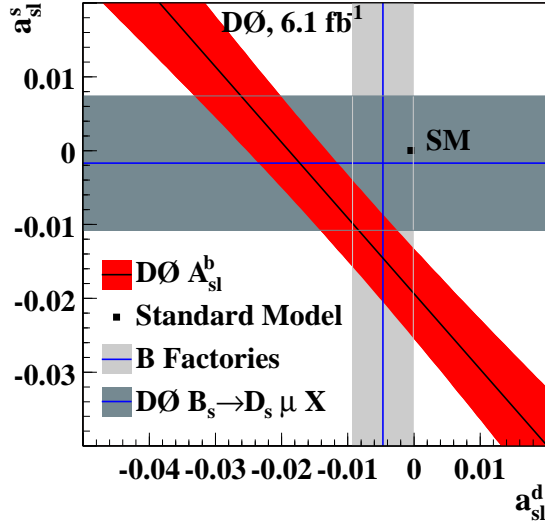


FIG. 3: (Color online) Comparison of A_{sl}^b in data with the SM prediction for a_{sl}^d and a_{sl}^s . Also shown are other measurements of $a_{sl}^d = -0.0047 \pm 0.0046$ [15–17] and $a_{sl}^s = -0.0017 \pm 0.0091$ [18]. The bands represent the ± 1 standard deviation uncertainties on each measurement.

B_s^0 mixing matrices, as given by Eqs. 3 and 4. Figure 3 presents our measurement of A_{sl}^b in the a_{sl}^d – a_{sl}^s plane, together with direct measurements of a_{sl}^d from the B -factories [15–17] and of our independent measurement of a_{sl}^s in $B_s^0 \rightarrow D_s \mu X$ decays [18]. Additional comparisons

and combinations of these results with previous measurements sensitive to the same physics effect are given in Ref. [5].

In conclusion, we have measured the like-sign dimuon charge asymmetry A_{sl}^b of semileptonic b -hadron decays:

$$A_{sl}^b = -0.00957 \pm 0.00251 (\text{stat}) \pm 0.00146 (\text{syst}). \quad (14)$$

This measurement is obtained from data corresponding to 6.1 fb^{-1} of integrated luminosity collected with the DØ detector at the Fermilab Tevatron collider. It is consistent with our previous measurement [14] obtained with 1 fb^{-1} and supersedes it. The asymmetry disagrees with the prediction of the SM by 3.2 standard deviations. This is the first evidence for anomalous CP violation in the mixing of neutral B mesons.

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